Consistency of extreme flood estimation approaches

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Abstract

Estimations of low-probability flood events are frequently used to plan infrastructure as well as to determine the dimensions of flood protection measures. There are several well-established methods to estimate low-probability floods. However, a global assessment of the consistency of these methods is difficult to achieve, as the "true value" of an extreme flood is not observable. A detailed comparison performed on a given case study brings useful information about the statistical and hydrological processes involved in different methods. In the present study, the following three methods of estimating low-probability floods are compared: a purely statistical method (ordinary extreme value statistics), a statistical method based on stochastic rainfall-runoff simulation (SCHADEX method), and a deterministic method (physically based estimation of the probable maximum flood PMF). These methods are tested for two different Swiss catchments; the results show that the 10,000 year return level flood estimations exceed the PMF estimations by 3% and 18%. The analysis shows that the plausibility of an extreme flood estimation does not only depend on the applied method, but also on its ability to represent flood-triggering processes including precipitation input, spatio-temporal precipitation distribution, and runoff.

Keywords: Extreme floods, FFA, PMF, flood frequency, method consistency

1. INTRODUCTION

Extreme flood estimations are required to calculate the dimensions of dams and flood protection measures for sensitive infrastructure such as nuclear power plants. Legal frameworks set protection requirements, which are usually either defined statistically, deterministically, or both. The statistical approach entails assigning an annual exceedance probability to a given discharge level. In case of sensitive infrastructure, this exceedance probability typically corresponds to a 10,000 years return level flood. The deterministic approach involves ensuring that infrastructure is safe in case the probable maximum flood (PMF) occurs. Particular guidelines for applying such approaches are defined in numerous legal frameworks for design flood estimation (for example ENSI 2013, FEMA 2012, FEMA 2013, FERC 2001, French Ministry of Ecology and Sustainable Development 2015, Official Journal of French Republic 2006, SFOE 2008).

The statistical approach typically entails generalizing an empirical distribution of a variable to a general distribution, with special regard to the tail of the distribution. The according variable is usually the annual maximum discharge or peak over a specific threshold. The approach in its original sense is expedient up to a return period that exceeds the sample size by a factor of 2 to 3 (see Coles 2004, Institute of Hydrology 1999, Klemeš 2000). The available discharge time series typically cover several years up to one century, which is insufficient for the design of big hydraulic structures typically requiring estimations for return levels of at least one thousand years. A number of techniques have therefore been introduced to overcome this limitation and allow for the estimation of less frequent events. One possibility is to extend the sample size, which can be done either through continuous modelling (e.g. Brocca 2011, England et al. 2013, Paquet et al. 2013, Saghafian 2014, Zoglat 2014) or through incorporating additional temporal, spatial, or statistical information (Kuchment and Gelfan 2011, Mediero et al. 2010, Merz and Blöschl 2008, Viglione et al. 2013). The here-cited studies have shown that such techniques have the potential to clearly improve statistical flood assessment. However, their applicability for extreme floods (e.g. return period >1 000 years) is still questionable for three reasons. First, these methods assume stationarity (Coles 2004), which is questionable due to trends in the meteorological input (Salas et al. 2014) and anthropogenic-induced changes of catchment characteristics (i.e. Brath et al. 2006, Ward et al. 2008). One possible way to overcome this problem is to use non-stationary models, an approach that has been applied in many case studies (e.g. Beguerìa et al. 2013, Silva et al. 2014, Sraj et al. 2016) but is controversial due to an associated increase in uncertainty (Serinaldi and Kilsby 2015). Second, such techniques theoretically allow for an infinite extrapolation of modelled extreme events, and the limits of their applicability remain unassessed. The techniques' underlying assumption of steady runoff conditions, however, is not necessarily valid due to non-linear runoff processes (Rogger et al. 2012) and inundation and retention effects (Felder et al. 2017). Third, statistical extreme flood estimations considerably exceed the range of observed peak discharges, which hampers a plausibility check on the estimated value and precludes a possibility for validation. Numerous national guidelines for extreme flood estimation require estimations for statistically defined return levels, e.g. 10,000 years, but do not provide any information on how such estimation has to be conducted. In consequence, extreme flood frequency estimations conducted by practitioners often do not reflect awareness of the applied methods' underlying assumptions and inherent uncertainties (Serinaldi 2015, Beven 2016).

The deterministic approach typically involves estimating an upper discharge limit, which corresponds to the concept of probable maximum flood (PMF) derived from the probable maximum precipitation (PMP). The PMP and the PMF are commonly used indices in planning hydropower dams. The PMP is defined as the "theoretical maximum precipitation for a given duration under modern meteorological conditions" (WMO 2009). An overview of the existing PMP estimation methods is provided by WMO (2009). In the course of scientific applications, PMP/PMF estimation methods have continuously evolved and improved. This is particularly the case when it comes to estimating the spatio-temporal PMP distribution (Beauchamp et al. 2013, Lagos-Zúñiga and Vargas 2014, Felder and Weingartner 2016), accounting for climate change and stationarity issues (Rousseau 2014, Stratz and Hossain 2014), and incorporating uncertainty bands (Faulkner 2016, Micovic et al. 2015, Rouhani and Leconte 2016, Salas et al. 2014). Although PMP estimation methods are continuously refined and commonly used by practitioners, there is still a controversial discussion on the underlying concept of PMP, namely on the legitimacy of an upper threshold of areal precipitation. This discussion has been comprehensively summarized by Salas et al. (2014) and Rouhani and Leconte (2016).

The PMP is an important variable for estimating PMF, which is defined as the "theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed" (WMO 2009). It is usually derived from hydrological models of catchment reaction to PMP input. Most government guidelines for practitioners recommend or prescribe using a unit hydrograph-based routing of the PMP to estimate the PMF (Smithers 2012). However, recent scientific applications make use of more sophisticated hydrological or coupled hydrological-hydrodynamic models (Beauchamp et al. 2013, Kienzler et al. 2015, Yigzaw et al. 2013, Yigzaw and Hossain 2016, Zeimetz et al. 2015). In addition, as is the case with PMP estimation methods, ongoing research aims at improving PMF estimation methods. Such efforts include incorporating and representing contributing processes (Ahmadisharaf and Kalyanapu 2015, Chen et al. 2016, Sen et al. 2017) and uncertainties (Felder and Weingartner 2017, Micovic et al. 2015, Salas et al. 2014). However, these clear methodical improvements fall short of overcoming the inherent lack of validation opportunities associated with the PMF concept.

The statistical and deterministic extreme flood approaches are therefore both hampered by high uncertainties and the inherent impossibility of assessing and validating resulting estimations. Nonetheless, numerous governments legally require an extreme flood estimation to be determined statistically (10,000 year flood), deterministically (PMF), or using both approaches. Although both approaches are frequently applied for planning purposes, little is known about the consistency of today's sophisticated extreme flood estimation methods. This is of particular importance because numerous methods for carrying out statistical or deterministic extreme flood estimations are continuously developed and advanced. In order to contribute to a better understanding of the statistical and deterministic approaches, the present study assesses two recently developed sophisticated estimation methods, one deterministic-statistical and one deterministic. Since an "implementation of strictly uniform criteria is not a possibility" (FEMA 2012), an improved understanding of these approaches facilitates further methodological development along with optimal use of available methods.

For this purpose, this study presents a detailed comparison of the two sophisticated extreme flood estimation methods. The assessed statistical approach, with a 10,000 year return level flood as a target value, is the SCHADEX method (Paquet et al. 2013). The examined deterministic approach involves using a Monte-Carlo framework to model PMP distribution combined with a coupled hydrologic-hydrodynamic rainfall-runoff model to estimate PMF (Felder et al. 2017). A comparison of these two methods is conducted in order to assess their potential strengths and weaknesses under the given conditions and more broadly to evaluate the two approaches under consideration.

Several integrative methods aim at effectively combine the statistical and deterministic approaches. The most obvious combinations entail assigning return periods to PMF estimations (Vogel et al. 2007, Harris and Brunner 2011), using percentages of the PMF (FEMA 2013), and applying upper-bounded distribution functions (Fernandes et al. 2010). However, these methods are questionable (FEMA 2013, McClenathan 2013) and do not help overcome the initial issues, namely the aforementioned lack of sample size and the limited representation of the processes associated with extreme events. Therefore such integrative methods are not covered in the present study.

2 STUDY AREAS AND AVAILABLE DATA

The present study was conducted using two different catchments, a high alpine and a pre-alpine catchment. The high-alpine Kander catchment covers an area of about 496 km^2, of which about 8% is glaciarized. It ranges from 650 to 3660 m a.s.l., with a mean elevation of 1900 m a.s.l. The catchment consists mainly of steep and high mountains punctuated by narrow valleys in which torrents drain the sub-catchments. This spatial set-up leads to a relatively short typical response time of 5-10 hours. The catchment outflow is usually relatively high in summer due to glacier melt contribution, and relatively low in winter when the bulk of the precipitation falls as snow. Extreme flows out of the catchment are mainly driven by intense rainfall events. The main river itself flows through a relatively narrow valley. The catchment therefore lacks widespread inundation and retention areas.

The second catchment under consideration is the Emme catchment, located in the northern pre-alpine region. The catchment covers an area of about 931 km^2, and its elevation ranges from 450 to 1400 m a.s.l. The mean catchment outflow underlies only slight seasonal changes, with a peak in spring when snowmelt contribution reaches its maximum, and relatively low flows in atumn. Extreme runoff occurrences in this catchment are mainly driven by precipitation, although some minor annual maximum discharges are also influenced by snowmelt. Compared to the above described Kander catchment, the Emme catchment has a bigger area, less steep mountain ridges and deeper soils, which expands the typical response time of the Emme catchment to 10-20 hours. A topographic map of the two catchments with their main tributaries is shown in Fig. 1.

Data availability is relatively good in both of the catchments. Hourly runoff data time series covering more than 35 years, as well as exact riverbed cross sections, were provided by the Swiss Federal Office for Environment. Runoff time series were available for the catchment outlets as well as for two internal sub-catchments within each catchment. Precipitation and temperature data for 38 stations in an hourly resolution covering more than 30 years were provided by MeteoSwiss. High resolved geospatial data representing the catchment characteristics were provided by Swisstopo.

3. METHODS

The purpose of this study is to compare the following two methods representing two fundamentally different extreme flood estimation approaches: the SCHADEX method for estimating a 10,000 year return level flood and the PMF-MC method for estimating a PMF. The fit of an ordinary general extreme value distribution (GEV) on observed annual maximum floods supports the interpretation of the results. An overview of the applied methods is provided in Table 1. The results of applying these extreme flood estimation methods on the two catchments under consideration are discussed in terms of plausibility, their representation of hydrological processes, and the consistency of the estimations.

3.1 Return level floods: The SCHADEX method

The SCHADEX method is based on the following two main components: a probabilistic rainfall model based on the MEWP (Multi-Exponential Weather Pattern) distribution method for weather pattern sub-sampling (Garavaglia et al. 2010, Garavaglia et al. 2011) and a semi-continuous stochastic rainfall run-off simulation (Paquet et al. 2013). Its application involves four steps, as described in the following paragraphs.

The first step is to build a weather pattern classification. Indeed, in the MEWP distribution, rainfall data are sampled according to a weather pattern (WP) classification which assigns each day of the observation period to a given weather type. This allows observations to be grouped into more homogeneous samples with similar synoptic origin. Usually, four to eight weather patterns are identified for a given region. An exponential model is fitted for each sub-sample above a given quantile (commonly 0.70). The MEWP distribution is finally built by composing all the individual exponential models based on the relative probability of each weather pattern. For the present study, the WP classification achieved for the South-Eastern part of France, detailed in Garavaglia et al. (2010), has been considered as relevant for Switzerland. In a few words, based on a wide dataset of long rainfall records across France, seven typical shapes of rain field shape of rainy days have been identified thanks to an ascending hierarchical clustering. The centroids of these rain field classes (along with a “no rain” class) have been projected in the geopotential height fields at 1 000 and 700 hPa (whose values has been extracted from the NCEP-NCAR reanalysis for vast a zone encompassing the South-West of Europe). Finally, each day of the 1948-2016 period has been assigned to a class (i.e. to a WP) thanks to its proximity to the centroids of classes in the space of geopotential heights. In the French classification used in this study, seven rainy situations (Atlantic circulation, Mediterranean flux, etc.) and one anticyclonic pattern were identified. The same WP classification is applied to all the stations of the considered area, here across Switzerland.

Once an areal precipitation is defined as a linear combination of daily rainfall records within the catchment, the second step is the fit of a relevant MEWP distribution to model the probability of rainfall over the catchment. Three or four seasons are defined, allowing months having similar precipitation distributions to be grouped. Seasonal MEWP distributions are then fitted as mentioned above.

The next step of the procedure is the rainfall-runoff stochastic simulation process. This is based on the MORDOR hydrological model. MORDOR is a lumped reservoir model in which the main hydrological processes are represented (Garavaglia et al. 2017), including snow accumulation and melting which have a significant influence in the studied catchments. In the present study, the model (and consequently the stochastic simulation process) were run at a daily time step, and a genetic algorithm-based tool with the discharge record at the outlet of the catchments was used to calibrate its parameters. A long-term climatologic record is used to generate a great variety of hydrological states (soil saturation and snow) through the MORDOR model. For each day of the climatologic record where precipitation has been observed, the actual precipitation is replaced by a three-day triangular synthetic event. This event is composed by a “big” rainfall (the central rainfall) flanked by lower values the days before and after (the adjacent rainfalls). By essence, annual maxima of daily precipitation are triangular events of this kind, thus this simple event generation fits the simulation of intense rainfall-driven floods. The generated sequence is simulated through the MORDOR model, and the maximum modeled daily discharge is stored with the probability of the rainfall event, computed using the MEWP model (for the central rainfall), completed by an ancillary model for the probabilities of the adjacent rainfalls relative to the central one. This step is repeated independently several hundred times for each rainy day of the climatological record, thus simulating about two million independent floods generated by precipitation events of all possible intensity. This process allows a quasi-exhaustive crossing of the precipitation scenarios with the antecedent hydrological conditions. The distribution of flood daily discharge is built with the maximum simulated values of each event, ordered and affected by their probability computed as mentioned before.

In the last step, a peak discharge distribution is derived from the daily discharge distribution with a peak-to-daily discharge ratio computed thanks a collection of hydrographs recorded at the outlet of the catchment. More detailed explanations on this process and its probabilistic hypothesis can be found in Paquet et al. (2013).

3.2 PMF: The PMF-MC method

The PMF is estimated by calculating the peak discharge that results from a PMP event (WMO 2009). This can be done by applying methods of various degrees of complexity in terms of spatio-temporal PMP pattern and rainfall-runoff modelling. A comparative study by Felder and Weingartner (2017) highlighted the dependency of PMF estimation on the choice of methods for spatio-temporal PMP representation as well as for rainfall-runoff modelling. The study underlines the necessity of the use of sophisticated modelling techniques in order to capture a range of processes that decisively influence PMF estimation. In line with the recommendations provided by Felder and Weingartner (2017), the PMF estimation for the present study was carried out using the following recently developed methods: a Monte-Carlo method for generating the spatio-temporal PMP distribution and a coupled hydrologic-hydrodynamic model for simulating the catchment reaction on the PMP input. This coupled approach is hereafter referred as PMF-MC.

The PMF estimation is based on the PMP estimation. For the present study, the seasonal PMP was estimated according to WMO (2009) guidelines. To generate the spatio-temporal PMP distribution, the Monte-Carlo method proposed by Felder and Weingartner (2016) was applied for the catchments under consideration. This method entails identifying discharge-maximizing precipitation distribution by feeding numerous patterns into a simple but efficient Unit-Hydrograph-based model. It is assumed that the spatio-temporal distributions that maximize discharge in the simple model are of further interest, namely for application in a more sophisticated modelling framework. For the present study, a number of 10^7 spatio-temporal

PMP distributions of a 72h event were generated for each catchment. Around 10^5 of them fulfilled pre-defined plausibility criteria in terms of temporal structure, spatial structure, and PMP threshold exceedance in sub-areas. To achieve this, the amounts of precipitation for every time period (time windows from 3h up to 72h) and area (from 1km^2 up to the full catchment size) were compared with a corresponding PMP estimation based on WMO (2009). Detailed information on the creation and assessment of such spatio-temporal PMP distributions is provided in Felder and Weingartner (2016). The event duration of 72h ensures that the precipitation event remarkably exceeds the typical response time of the catchments, and therefore no discharge-maximizing spatio-temporal precipitation distributions are missed. Out of this sample, 1 000 discharge maximizing PMP distributions were identified. These discharge-maximizing PMP distributions were then fed into a coupled hydrologic-hydrodynamic model in order to conduct a detailed assessment of the catchment reaction to the PMP. For this purpose, the hydrological model PREVAH (Viviroli 2009a) was set up for the tributaries of the main river. PREVAH is a semi-distributed conceptual model that calculates on hourly time steps based on hydrological response units (HRUs). A detailed description of the model is provided by Viviroli (2009a). There are 12 free parameter to calibrate (14 in case of glaciated catchments like the Kander catchment). The gauged sub-catchments were calibrated at hourly time-steps using the latin hypercube algorithm provided by PEST (Doherty 2014). The ungauged sub-catchments as well as the areas that drain directly into the main river were calibrated using a parameter regionalization method provided by Viviroli (2009b, 2009c). An overview of the calibration and validation periods for each sub-catchment and the corresponding skill-scores is provided in Table 2 (Kander catchment) and Table 3 (Emme catchment). The outputs of the hydrologic model were used as upper boundary conditions for the hydrodynamic model BASEMENT-ETH (Vetsch et al. 2017), which was set up for the main rivers. Coupling a hydrodynamic domain is important because of the influence of inundation and retention effects occurring along the main river (Felder et al. 2017). Each of the 1 000 tested spatio-temporal PMP distributions was used to create a hydrograph (hereafter referred to as a PMF scenario). Finally, the PMF was based on the scenario with the highest peak discharge.

3.3 Return level flood: GEV-distribution fit

The simplest method for the estimation of return level floods considered in this study is an ordinary fit of a distribution function to an empirical sample of annual maximum floods. The method allows for the estimation of flood return levels that exceed the sample size by a factor of 2 to 3 (Coles 2004). In consequence, the method does not provide a reliable benchmark for extreme flood estimations in the upper-most part of the tail distribution. In contrast to the two aforementioned methods, SCHADEX and PMF-MC, this method is purely data driven, and its application requires little effort. Practitioners therefore often apply it for design flood estimation, although misconceptions and disregard of the valid range of application are common (Serinaldi 2015). In the present study, a GEV was fitted for annual maximum discharges, separately for both catchments under consideration. For this purpose, the Swiss Federal Office for Environment (FOEN) provided gauging time series that cover 34 years (Kander) and 93 years (Emme). The same procedure was conducted for the 72h areal precipitation sum. In this case, annual maximum 72h areal precipitation sums were extracted from the RhiresD-reanalysis dataset (MeteoSwiss, 2016), which covers 43 years.

4 RESULTS

The resulting estimates for rainfall and for peak discharges are summarized in Fig. 2. For the alpine Kander catchment, the MEWP precipitation estimates are relatively close to the observed values and to the fitted GEV distribution, although a slight underestimation of the tail distribution can be recognized. The MEWP estimate for the 10,000 year return level precipitation (296mm) lies significantly below the PMP estimation (396mm). A similar pattern resulted from the precipitation estimation for the pre-alpine Emme catchment. Again, the MEWP estimation is close to the GEV fit and slightly underestimates the highest observed values. The PMP estimation (346mm) exceeds the MEWP estimation for the 10,000 year return level (230mm) precipitation significantly, yet not exorbitantly.

The corresponding peak discharge estimations are shown in the bottom part of Fig. 2. In case of the Kander catchment on the lower left, the SCHADEX curve fits well to the observed values and to the corresponding GEV fit. The SCHADEX estimation for the 10,000 year return level flood amounts to 851 m^3s^{-1}, which is above the PMF estimation of 830 m^3s^{-1}. The peak discharge estimations for the Emme catchment are similarly consistent. The GEV fit on the observed values results in relatively high residuals in the upper range of the empirical distribution, meaning that the GEV distribution does not appropriately represent the empirical distribution of the annual peak discharges. Moreover, the shape parameter of the fitted GEV distribution is negative and therefore corresponds to an upper-bounded distribution, which does not represent the shape of the upper tail of the empirical distribution (Kochanek et al. 2014). In comparison to a simple GEV fit, the SCHADEX estimation relies on models calibrated with the highest observed discharges (both for precipitation and discharges). This points to the importance of focusing on the highest observed events, which are of particular interest for extreme flood estimation. In consequence, the SCHADEX estimation better fits the upper range of the empirical distribution, and therefore better represents the events of particular interest. This leads to a bigger tail in the estimated distribution and therefore to differences in the estimation of return level floods. In the case of the Emme catchment, the values for the 100-year return level flood are 620 m^3s^{-1} using an ordinary GEV fit and 806 m^3s^{-1} according to the SCHADEX method. When comparing the results of the SCHADEX estimation with the PMF estimation, the relatively large upper tail of the distribution generated with SCHADEX leads to an exceedance of the PMF estimation. For the 10,000 year return level flood, the PMF estimation of 1388 m^3s^{-1} is exceeded by the SCHADEX estimation of 1635 m^3s^{-1}. This exceedance of the PMF value shows an inconsistent behavior of these two methods under consideration.

A comparison of the resulting extreme flood estimations and observed events is shown in Fig. 3. The data of the observed events are derived from stations that are within or close to the according catchment. Weingartner (1999) estimated the corresponding regional envelope curves based on the highest observed events, which are also shown in Fig 3. The comparison indicates that the SCHADEX estimations are generally plausible; the 100 year return level flood lies on or slightly below the envelope curve. The estimations for the 1 000 and for the 10,000 year return level floods lie significantly above the curve. The PMF estimations also lie significantly above the corresponding values on the envelope curves, but are not more than three times higher. The range of peak discharges that result from the PMF scenarios shows that PMF estimations depend considerably on the spatio-temporal PMP distribution.

5 DISCUSSION

The results show that the plausibility of an extreme flood estimation does not only depend on the applied method, but also on its ability to represent flood-triggering processes including precipitation input, spatio-temporal precipitation distribution, and runoff.

5.1 Representation of precipitation

In comparison with the highest observed precipitation amounts in each catchment, the MEWP method leads to plausible estimations as the GEV curves fit on observed values and the MEWP estimations do not deviate systematically. This aligns with the findings of Garavaglia et al. (2011) who empirically showed the robustness of the MEWP method for daily precipitation events. For the 72h events in this study, there are minor differences between the MEWP-generated quantiles and the observed quantiles, possibly because the distribution of extreme values is adjusted to daily values and complemented with an anciliary probabilistic model to build 72h distributions. In addition, the MEWP distribution incorporates seasonal empirical quantiles, whereas there is no distinction between different seasons of the observed values in Fig. 2. The ratio between the 10,000 year return level precipitation depth estimated by MEWP and the PMP estimation can be considered reasonable when compared with results obtained by WMO (2009) and Lagos-Zúñiga and Vargas (2014). Regarding the spatio-temporal structure of the rainfall events, there are considerable differences between the two methods under consideration. The MORDOR lumped hydrological model only considers a uniform areal precipitation (and consequently the MEWP model fitted to it) and a very basic temporal pattern for simulated events (three day event with a high central rainfall adjointed with two lower values before and after). In contrast, the PMF-MC method allows for a more finely resolved spatial distribution over a number of sub-catchments and an hourly based temporal structure. Although Nicotina et al. (2008) found that a proper estimation of the rainfall depth is the key factor for extreme flood estimation, recent studies confirmed that the spatio-temporal rainfall patterns can significantly affect the modelled peak discharge (e.g., Adams 2012, Seo 2012, Lobligeois 2014, Paschalis et al. 2014). However, the spatio-temporal coarseness of the rainfall events simulated by SCHADEX is compensated by the high number of simulated scenarios, as approximately $2x10^6$ events are considered. In contrast, the PMF-FC method considers only 10^3 out of 10^7 generated spatio-temporal distributions. This is mainly due to significantly longer computation times. A study by Felder and Weingartner (2017), however, showed that the choice of rainfall pattern representation does not necessarily affect an extreme flood estimation in a negative way, provided the methods for spatio-temporal precipitation distribution and for rainfall-runoff modelling are of similar complexity.

Although the two sophisticated methods under consideration are based on the same raw data, the concepts of the estimations are fundamentally different. Nevertheless, the resulting estimated rainfall depths lie within a relatively narrow and acceptable range, and the ratio between the estimations is reasonable. This is evidence that the methods under consideration lead to plausible extreme precipitation estimations.

5.2 Representation of rainfall-runoff processes

Various processes can dominate flood events in the two catchments under consideration. For the two catchments under consideration, the most important when it comes to extreme floods are purely rainfall-driven events, although snowmelt can contribute in a lesser extent. The following three aspects of a method largely determine the representation of flood-generating processes for an extreme flood estimation: the model complexity, the spatial and temporal representation of the input data, and the modeling strategy (e.g. how seasonality and antecedent conditions are incorporated). The choice of model type and model complexity determines the representation of such flood-generating processes, and therefore influences the plausibility of the resulting estimation.

The pure statistical estimation method, namely the fit of a GEV distribution to empirically derived flood peaks, is lacking in terms of process representation. Such estimations usually do not consider seasonality or differing antecedent catchment conditions. Moreover, several choices regarding the empirical values influence the resulting estimation. The method is applied either on annual maximum discharges or on discharges that exceed a certain threshold, and the temporal resolution of the underlying empirical data typically ranges from 10 minutes to one day. In consequence, the resulting estimation depends not only on data availability, but also on the selected empirical sample.

The hydrological model MORDOR, which is used for the SCHADEX estimation, calculates discharge on a catchment scale and on a daily basis in the considered catchments. Although all of the major flood-contributing processes are captured, the structure and resolution of the model requires some simplifications in process representation. The model allows for various antecedent catchment conditions and seasons to be considered. This is also represented in the SCHADEX procedure (by simulating events with any of the observable antecedent conditions of the catchment), and in the MEWP models, built for three to four distinct seasons to account for the seasonal variability of the rainfall intensities.

The hydrologic model PREVAH, used for PMF estimation, calculates spatially semi-distributed and at hourly time steps (Viviroli 2009a), which allows for more detailed modelling of contributing processes than what the MORDOR model is capable of. The semi-distributed model design and the hourly time steps enable consideration of more finely resolved input data as well as a more detailed conceptual process description. As is the case in the SCHADEX estimation, seasonal differences of precipitation extremes and antecedent conditions are considered in the PMF-MC method.

Figure 4 schematically illustrates the importance of proper hydrological process representation, which allows for the modelling of complex combinations leading to a global distribution of flood events, on the example of snowmelt-driven and rainfall-driven events. On the left, the fit of a distribution function on an empirical distribution of flood peaks is conducted without any consideration of underlying processes. In this case, the residuals are relatively high, and the fitted distribution does not appropriately represent the empirical distribution. On the right, the empirical distributions are separated according to the flood-triggering process, and there is a separate distribution function fitted for each process. The example can also be applied to other flood-triggering processes with differing flood event characteristics. The SCHADEX method with its seasonally different initial conditions and rainfall statistics provides enough flexibility to capture such differences.

5.3 Representation of hydrodynamic processes

In pure statistical extreme flood estimation, hydrodynamic processes are not represented and thus not directly considered. The SCHADEX method is based on hydrological modelling of precipitation scenarios, and therefore does not consider inundation and retention effects. In contrast, the PMF-MC method includes hydrodynamic modelling and therefore better accounts for peak dampening processes. The occurence of hydrodynamic processes can significantly influence flood peak discharges due to widespread inundation and retention effects (Felder and Weingartner 2017) and new flow paths (Lammersen et al. 2002, Huang et al. 2007, Vorogushyn et al. 2012). Such effects are likely to occur in cases of extreme floods that significantly exceed the design values of flood protection measures. Moreover, using a hydrodynamic model domain enables mapping of flood-prone areas within the catchment under consideration (Cook and Merwade, 2009), and therefore enables comprehensive plausiblity checks. However, the application of a hydrodynamic model is relatively time-consuming compared to ordinary hydrologic modelling. In consequence, fewer scenarios can be considered for an estimation. In the present case, the calculation time for one extreme flood scenario differs by a factor of 10^3.

As retention and inundation processes generally have a dampening effect on extreme peak discharge, the modelled results are expected to be lower when a hydrodynamic domain is applied. This statement is supported by the results shown in Fig. 2, where the SCHADEX estimation for the 10,000 year return level flood exceeds the PMF estimation.

5.4 Overall consistency

The results show the importance and the great interest of comparing such approaches, giving some clues about the plausibility of each estimation and pointing to key processes that impact estimations. Regarding precipitation, in both cases the estimated 10,000 year return level event is relatively close to the estimated PMP but does not exceed it. Moreover, the resulting estimations are within a reasonable range. Considering that the MEWP method and the PMP-MC method are based on fundamentally different concepts, the results indicate consistent behaviour of their estimations. Regarding extreme peak discharge, estimations for the alpine Kander catchment are consistent. However, there are some distinct differences in the case of the pre-alpine Emme catchment. First, the fit of a GEV on the empirical distribution of annual maximum discharges shows high residuals, particularly in the upper part of the distribution. This is due to the equally weighted influence of all empirical values on the shape of the fitted distribution. The non-extreme annual maximum discharges are not of particular interest for extreme flood estimation, but they have a remarkable influence on the shape of the distribution in the upper tail. This effect leads to high residuals between the highest observed events and the fitted distribution. Moreover, the GEV fit for the Emme catchment is upper-bounded and therefore does not sufficiently represent the empirical distribution. In this case, application of this method without any further analysis would lead to highly questionable conclusions. The SCHADEX method enables a more targeted weighting of the highest observed events and a better representation of the most extreme events within the sample of empirical annual maximum floods. The method allows different underlying processes that cause extreme flood events to be distinguished. However, the underlying statistical concept theoretically enables an infinite extrapolation of extreme events, without consideration of upper thresholds. For example, as the results for the extreme discharge of the Emme catchment show, an estimation of a 10,000 year return level event may exceed the estimation of an upper limit of discharge. Complementary information, for instance as provided by a PMF estimation, therefore adds useful information about the catchment behaviour in case of rare extreme events.

Both extreme flood estimation approaches, statistical and deterministic, provide potentially valuable information for planning and protecting sensitive infrastructure. Using sophisticated methods like SCHADEX and PMF-MC can yield plausible and consistent results. As there is no possiblity to validate estimations for rare extreme events such as the 10,000 year return level flood and the PMF, cross-checking estimations based on fundamentally different concepts contributes deeper knowledge on extreme floods. The inconsistency in the case of the Emme catchment is an exemplary example of how a strict application of an extreme flood estimation method while neglecting underlying processes can result in misleading estimations. As both of the approaches under consideration have specific strengths and weaknesses, it is of high importance to question the results derived using any of the methods. The resulting estimations for the Emme catchment show that understanding flood-triggering processes is crucial for interpreting results of both extreme flood estimation methods. Therefore, not only consistency but also plausiblity must be considered when evaluating extreme flood estimations. This is in line with the guidelines of WMO (2009), which state that "*it should not be a requirement that PMP/PMF should be larger than or smaller than a storm/flood with a defined frequency*", as long as the estimations are undertaken in a reasonable manner.

6 CONCLUSIONS

Extreme flood estimations for two different catchments were conducted using two different estimation approaches, represented by rather sophisticated estimation methods. The approaches allow for estimations with different target values to be conducted. The SCHADEX method was applied to estimate peak discharges of given return periods, and the PMF-MC method was applied for PMF estimation. The resulting estimations were compared with a focus on plausibility and consistency. The results show that there is some discrepancy between the resulting estimations due to the methods' different representations of the catchments and underlying processes.

In view of the fundamentally different concepts behind the different approaches, the results are of acceptable consistency. The combination of sophisticated extreme flood methods therefore allows for reliable estimation, whereas estimations of return level floods and PMF events deliver complementary information. In combination, they allow for a more comprehensive assessment of extreme flood events than the application of a single method.

Acknowledgements

The authors would like to thank EDF for providing the SCHADEX tools and for granting support in the tools' application. Data were provided by the Swiss Federal Office of Environment FOEN, the Swiss Federal Office for Topography swisstopo, and the Swiss Federal Office for Climatology and Meteorology MeteoSwiss.

Funding

This study was funded by the Mobiliar Lab for Natural Risks.

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Method	**GEV-fit**	**SCHADEX**	**PMF-MC**
Approach	Statistical	Statistical + Deterministic	Deterministic
Target value	~100y flood	10,000y flood	Probable maximum flood
Precipitation	-	MEWP	PMP-Monte Carlo
Hydrological model	-	MORDOR	PREVAH
Hydrodynamic model	-	-	BASEMENT-ETH

Table 1: Overview of the applied methods.

Kander Hondrich	**Coupled model (PMF-MC)**		**MORDOR (SCHADEX)**	
Sub-catchment	Calibration period	NSE	Calibration period	NSE
1 (KanFru)	2007-2014	0.81	no sub-catchments	
2 (EngFru)	2007-2014	0.76		
3 (KieRei)	regionalized parameter			
4 (KanHon)				
Full catchment	**2007-2014**	**0.85**	**1998-2014**	**0.86**

Table 2: Skill-scores of the applied models for each sub-catchment and for the full Kander catchment (NSE according to Nash and Sutcliffe (1970).

Emme Wiler	**Coupled model (PMF-MC)**		**MORDOR (SCHADEX)**	
Sub-catchment	Calibration period	NSE	Calibration period	NSE
1 (IlfLan)	2007-2013	0.69	no sub-catchments	
2 (EmmEgg)	2007-2013	0.74		
3 (EmmBur)	regionalized parameter			
4 (EmmWil)				
Full catchment	**2007-2013**	**0.79**	**1998-2014**	**0.77**

Table 3: Skill-scores of the applied models for each sub-catchment and for the full Emme catchment (NSE according to Nash and Sutcliffe (1970).

Figure 1

Click here to access/download;Figure;Fig1.tif

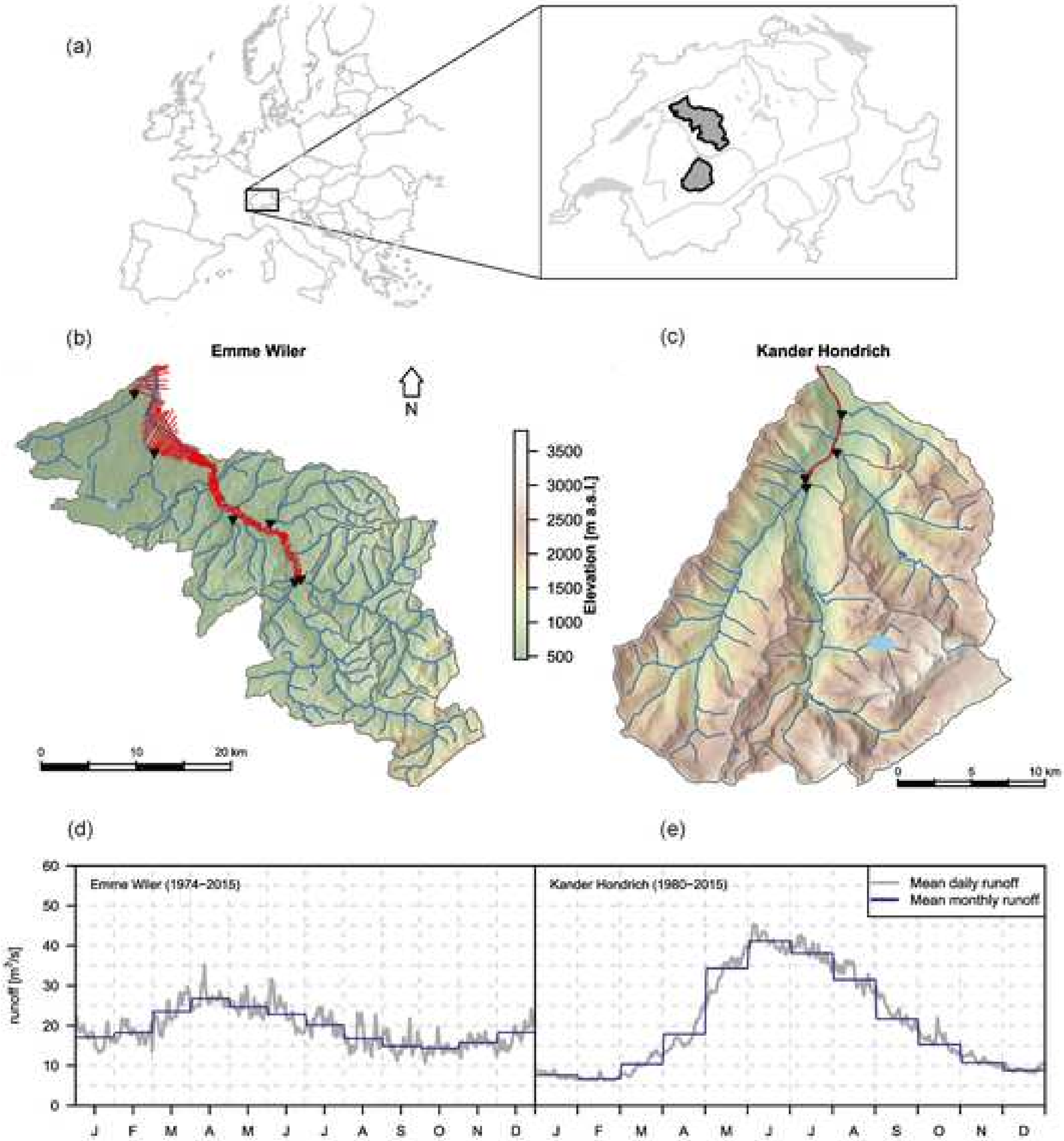

Fig2

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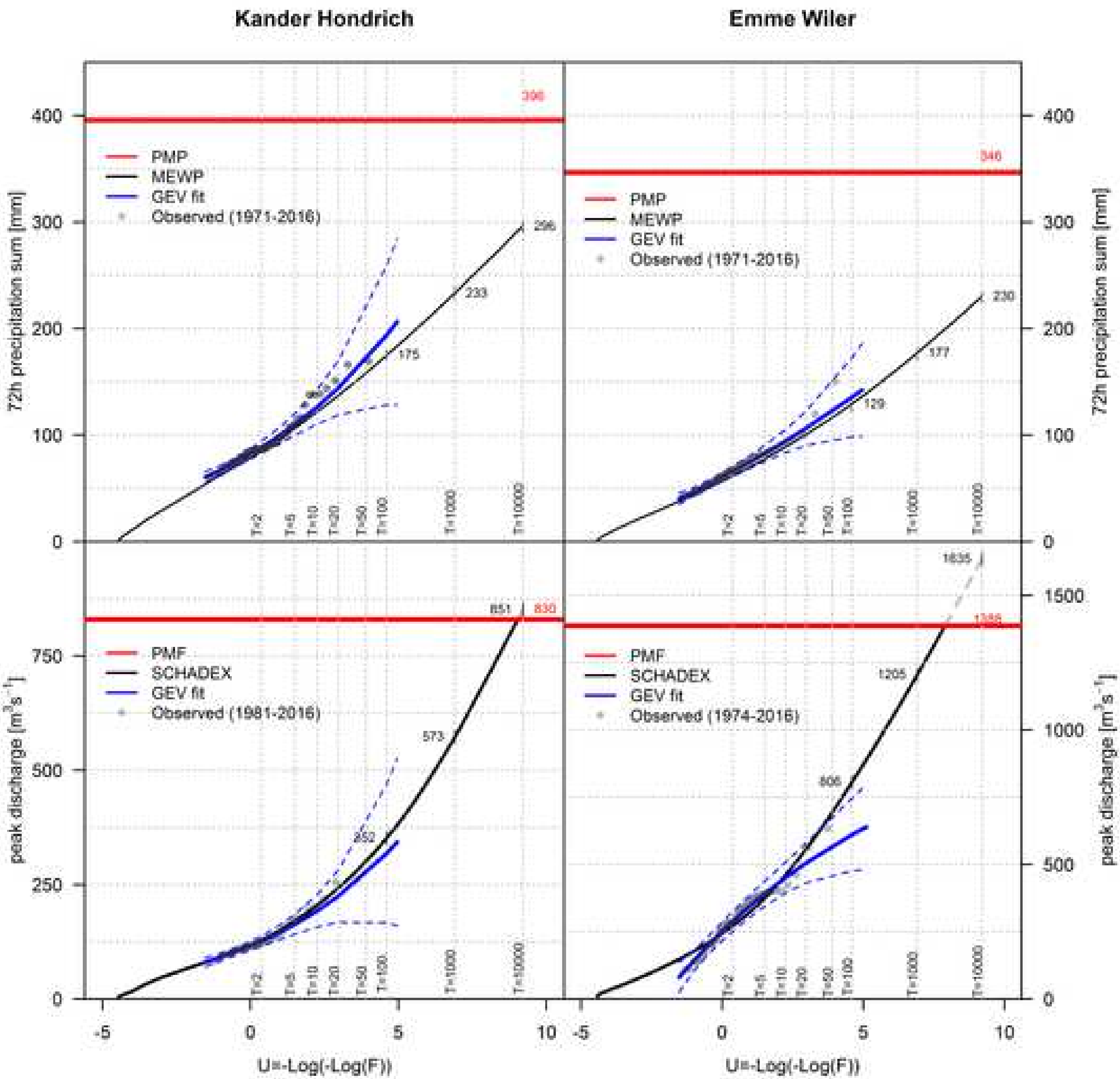

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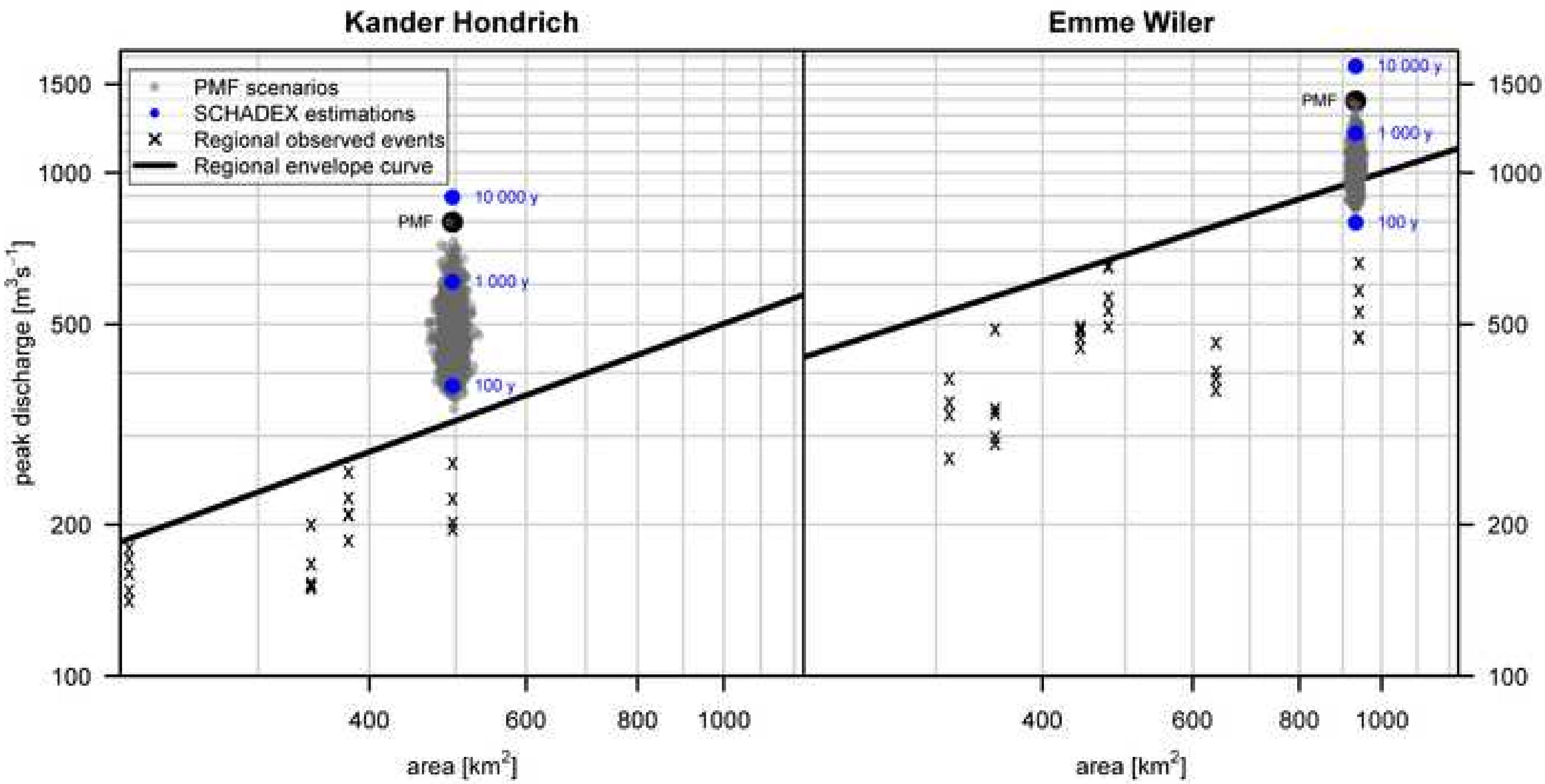

Kander Hondrich
Emme Wiler
PMF scenarios
SCHADEX estimations
Regional observed events
Regional envelope curve
10 000 y
PMF
1 000 y
100 y
peak discharge [m3s-1]
area [km2]
100
200
500
1000
1500
400
600
800
1000

Figure 4

Click here to access/download;Figure;Fig4.tiff

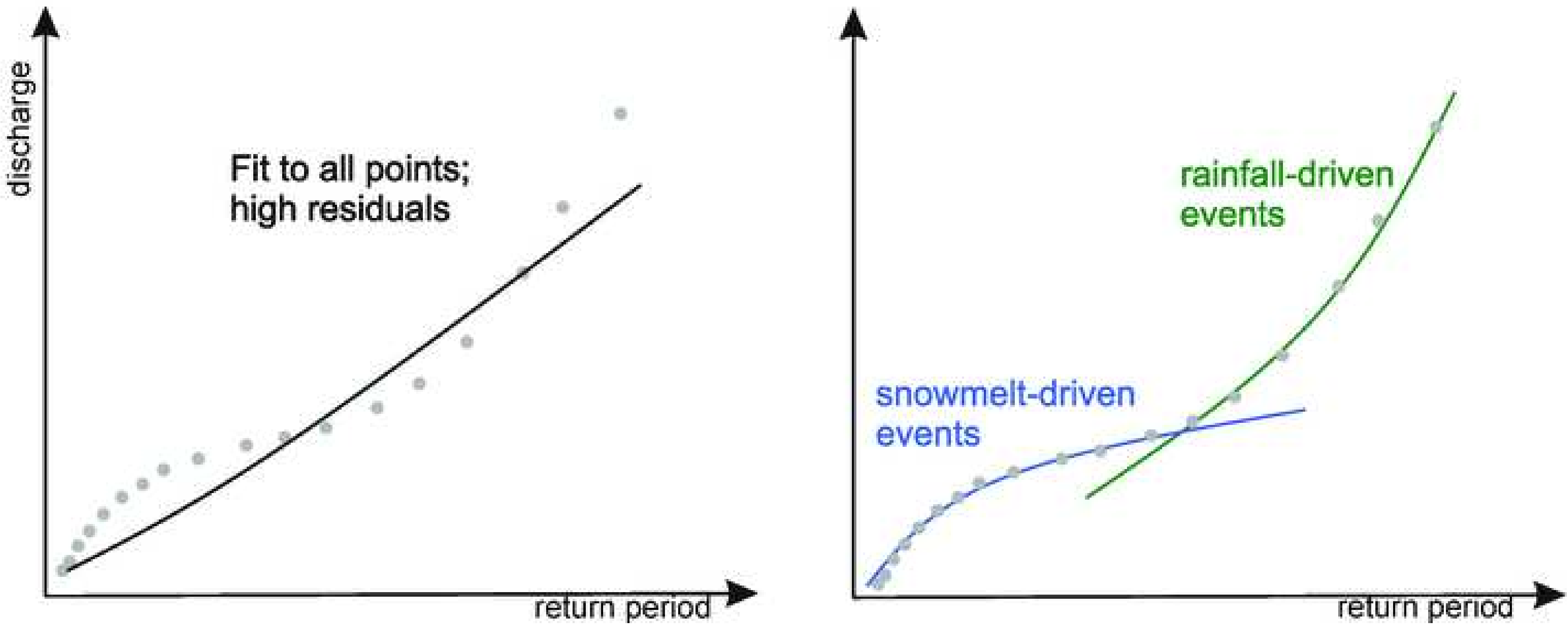

Figure Caption List

Figure 1: Location (a), topographic maps (b, c) and runoff characteristics (d, e) of the two catchments under consideration (Data provided by swisstopo). The triangles in the bottom maps (b, c) indicate the coupling points between the hydrological and the hydrodynamic model.

Fig. 2: Summary of the resulting estimations for the Kander catchment (left) and the Emme catchment (right). The upper plots show the method comparison for precipitation input, the lower plots show the corresponding peak discharge estimations. The variable F represents the non-exceedance probability, e.g. a value of 0.99 for a return level of 100 years.

Fig. 3: Derived peak discharge estimations compared to the highest observed flood events within or near the corresponding catchments, along with regional envelope curves presented by Weingartner (1999).

Fig. 4: Schematically shown influence of process representation on the extrapolation of return level floods.